Acacia tortilis encroacher bush as a bioenergy source

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Abstract*— Invasive and encroaching (IE) species have posed a threat to biodiversity in ecosystems, rangeland productivity, groundwater generation, the environment and economy is savannah ecosystems like Botswana and Namibia. While de-bushing of large diameter stocks have yielded huge economic returns for countries like Namibia through a lucrative charcoal and fuelwood or chips, smaller diameter ones usually have no economic value, especially shrubs that encroach space in cities and towns. The goal of this study is to explore possible means of deriving economic value from the encroachers, which are currently disadvantaging Botswana through reduced rangeland productivity and de-bushing costs. Pyrolysis has received attention as a potentially low cost thermochemical method that can efficiently utilize such lignocellulosic residues. The primary goal is to use the bio-oil in stationary engine applications for power generation, especially in remote areas of sparsely populated Botswana, where it has been deemed uneconomic to connect them to the national grid. Characterization of encroacher bush indicated it could be a good feedstock for pyrolytic conversion due to the relatively high volatile matter (76.51%) , moderately low ash content (3.90%) and high gross calorific value (17.3 MJ/kg). This *A. tortilis* was then pyrolyzed under varying overall and condenser temperatures to establish the optimum operating parameters. The obtained bio-oil was characterized, comparing its properties to conventional fuels. The optimum pyrolysis temperature was found at 550^{o}C, while the optimum primary condenser temperature with the best quality oil (36.809MJ/kg), was at 125^{o}C. The viscosity of this oil was estimated to be 24.024 mPa.s using the other characterized samples. Gas chromatography was also carried out on the oil samples and the compounds with the highest mass presence were catalogued. It is concluded that the bio-oil could be used in moderate-slow engines with moderate upgrading, while it needs to be diluted with a solvent then blended with a diesel for use in fast diesel engines. It is also important to establish the particulate composition and flash point of the bio-oil, though these tests were not carried out in this study.

Keywords-component; formatting; style; styling; insert (key words)

I. Introduction (Heading 1)

The proliferation of invasive and encroaching (IE) species has emerged as a threat to biodiversity in ecosystems, rangeland productivity, groundwater generation, the environment and economy at large [1], [2]. These IE species are characteristically fast growing and have to be controlled through mechanical or chemical methods which cost a lot of money and effort. For smaller shrubs not useful for wood or charcoal making, there is usually little or no benefit derived from such de-bushing exercises. De-bushing and heaping IE biomass usually leads to a greater propagation of the species through propagule pieces.

This study particularly focuses on bush encroachment, a term that refers to the proliferation of native woody biomass on grazing land, choking undergrowth. Invasive species is a more generic term referring to, especially, foreign biomass that takeover land or water bodies and threaten both plant and animal bio-diversity. Bush encroachment has been widely documented for savanna ecosystems in places like Botswana [3]–[5] and Namibia [6], [7]. According to research, in the case of Namibia, 26-30million hectares of land are encroached, inducing up to N$700million loss of income annually (~US$48,4million p.a) [6].

Meanwhile, global initiatives in renewable and sustainable energy have identified biomass as a potential feedstock for bioenergy and second generation (2G) biofuel production, especially when wastes are used to avoid direct or indirect interference with food security. Reza et al. (2019) note that very few studies have been made to evaluate the potential production of 2G biofuels from IE species [1]. This research seeks to expand this knowledge space around IE species, with a particular focus on *Acacia tortilis*. Since the objective is to map the bio-energy potential of *A. tortilis* relative to other biomass, a general characterization is initially done. The characterization is followed by an experimental study of the pyrolysis route, as a potentially low cost route of exploiting this resource for power production.

II. BOTSWANA CONTEXT AND THE CASE OF ACACIA ENCROACHERS

Charis et al. (2019) reviewed the effect of bush encroachment in Botswana qualitatively, implicating drought hardy plants like *A. tortilis*, *A. erubescens, A. mellifera and Dichrostachys cinerea* [2]. These effects include reducing pastoral productivity, biodiversity, generation of groundwater and the aesthetic appeal around towns, cities, highways and water sources. Evidently, the Acacias are the dominant encroacher. Reza et al. (2019) remarked that Acacia species are notorious for their invasive nature and disruption of biodiversity [1]. They provided a figure showing regions occupied by 1350 species of Acacia, which thrive in warm, tropical or desert climates. Charis et al (2019) however, noted that the tree or bush dimensions determine their biomass to bioenergy (BtB) applications [2].

Fig 1. **Left**- Acacia encroacher shrubs; **Right**- Dry, debushed encroacher *A. tortilis* shrubs in a Botswana town

For instance, both Charis et al (2019) and Reza (2019] document cases of short shrubs (25-200cm) of small diameters (see Fig 1), which may not be suitable for use in charcoal making, but could still be chipped, briquetted and/or pyrolyzed. On the other hand, Ahmed et al. (2018), Ahmed et al 2018 (1) and Simmonds (2012) talked of larger acacias +/- 300cm tall that can be carbonized for charcoal, but are still eligible to chipping, briquetting and pyrolysis [6], [8], [9]. Ultimately, the choice route should be justifiable in terms of cost-effectiveness given the feedstock nature, socio-economic need, sustainability and potential environmental, economic and socio-economic and environmental benefits. For instance, the domestic initiative for carbonization and briquetting of biomass for domestic applications derive momentum from global SDGs around cleaner domestic fuels; while mini grid solutions would require either traditional CHP or more advanced methods like pyrolysis of gasification. Mini grid solutions could be an alternative to solar systems, especially for heavy duty energy supply in remote villages within Botswana, which are detached from the main grid [10]. The sparsely distributed population within extensive Botswana makes it economically unjustifiable to connect some remote, small villages to the main grid. It is with this in mind that the bio-oil potential of *A. tortilis* will be explored, with a target application of stationary fuel oil generator sets for power generation. While regions with access to ports envisage that one of the close-to-be commercialized applications of bio-oil that does not need rigorous upgrading will be as fuel for marine engines, landlocked and developing regions like Botswana, in Africa, could prioritize energy solutions [11].

III. METHODOLOGY

A. *Characterization of feedstock*

For bioenergy projects to be sustainable, there has to be adequate knowledge of the supply capacity and the suitability of the biomass properties for thermochemical conversions [12]. To determine the quality of the biomass, the proximate, ultimate and calorimetric analyses were conducted. Dry *A. tortilis* shrubs were ground using a JF 2-D chopper & hammer mill with a 0.8mm sieve. The mill product was further sieved to obtain a size below 250µm for characterization. The American Society of Testing Materials (ASTM) standards were used

Proximate analysis- The proximate composition for moisture content (MC), volatile matter (VM), ash and fixed carbon (FC) was determined using a Leco 701 thermogravimetric analyzer (TGA). It was set according to ASTM E871 for MC, E897 for VM and E830 for ash and FC. To determine MC, the TGA was ramped at 6ºC/min from ambient temperature to 107 ºC, then maintained there in a nitrogen atmosphere until a constant mass was achieved. For the VM, the TGA was then ramped at 37ºC/min to 550ºC then maintained there under an inert nitrogen gas environment until a constant mass registered. Subsequently, the lids were removed from sample crucibles according to the set program, then the samples were reheated to 550ºC and maintained at that point in an oxygen rich atmosphere to ash the samples. This procedure determines the FC as the matter that reacts with oxygen and the ash as the remaining substance. The proximate composition was established by taking an average of 3 samples.

Ultimate analysis- To determine the carbon, hydrogen, nitrogen and sulphur content in the *A. tortilis* samples a Flash 2000 CHNS analyzer (ThermoFisher Scientific, USA) was used. The total oxidation method was employed, where the combustion gases were separated by gas chromatography and the CHNS % compositions calculated. The O% composition was determined by difference. Two runs were conducted and the averages were considered.

Calorimetry- The ASTM D5468–02 procedure was followed to determine the higher heating value (HHV) of the *A. tortilis* using a bomb calorimeter CAL2K-2 calibrated using benzoic acid. Two runs were conducted and the averages were considered.

B. *Pyrolysis experiments*

In mapping the bioenergy potential of the *A. tortilis*, beyond knowing the properties of the feedstock, it is important to obtain the optimum yield and quality of bio-oil. The initial tests on this newly explored feedstock have covered pyrolysis temperature as the basic and most influential variable on bio-oil yields [13]. The variable is then also used on the primary condenser as a basic upgrading technique to improve the quality of the oil. Prior to the pyrolysis pilot runs, the acacia feedstock was ground using a hammer-chopper mill with a 5mm sieve. A size range between 1.70mm and 5.00mm was then screened for pyrolysis using the right sieves.

Optimum pyrolysis temperature- A mass between 200 and 220g of *A. tortilis* was placed inside the reactor. The set points for the primary and the 2 secondary condensers were adjusted to 125ºC and 25ºC respectively. The system was purged for 2 minutes using inert (Nitrogen) gas. The furnace system was turned on and ramped at 66ºC/min until the 450ºC set point, which was then maintained until the end of the run. The experiment was left to run until the scrubber had no more bubbles then stopped on the SCADA software. The solid and liquid yields were then determined by measuring and weighing the collected liquids and chars. The experimental runs were then repeated for 500 ºC, 550 ºC and 600 ºC. The optimum pyrolysis temperature was considered to be the one with the highest bio-oil yield.

Optimum primary condenser temperature- The procedure for these experiments to determine the optimum primary condenser temperature was the same as the previous, save for the fact that they were all done at 450ºC, with the primary condenser temperature varied at 90ºC, 100ºC, 110ºC, 125ºC and 140ºC. The optimum primary condenser was considered as that yielding bio-oil with the highest specific gravity, indicating a small aqueous fraction present.

C. Characterization of products

The product of interest in the characterizations was the bio-oil, primarily for use as a fuel in stationery diesel then secondarily for potential applications in vehicle engines. It is important then, to compare the properties of the oil to diesel and fuel oil. The calorific value of the residual biochar is also determined.

The physico-chemical properties of the bio-oil are important since they determine if fuel can be used sustainably in unmodified without damaging the parts through erosion or corrosion. The pertinent properties measured in this regard were the pH, viscosity and the specific gravity (SG). The pH was measured using a JENCO pH 6810 meter calibrated with pH4.00, 6.86 and 9.18 solutions. The viscosity was measured using a Thermoscientific Haake viscotester E with an R7 spindle. The SG was determined by dividing the mass of sample with volume obtained and expressing the result as a ratio to the density of water. The SG was used as an approximate indicator of the aqueous composition, since there was no Karl Fischer titrator for determination of water content.

The bio-oil samples were also characterized for thermal and fuel properties, specifically the high heating value, using a bomb calorimeter IKA C1. Only the samples collected under the primary condenser could be tested, since secondary condenser products had a high water content making it difficult for combustion, even with over 50 w/w% of a combustion aid. The samples were placed in a crucible along with a fuse attached to the ignition wire, then the enclosed system was subjected to a run according to the DIN 51900 standards. Most of the primary condenser oil samples collected above 100ºC did not require any combustion aid, however for the 90ºC and 100ºC samples, a diesel sample was added to constitute between 40% and 80% of the mixture composition by weight.

IV. RESULTS AND DISCUSSION

A. Characterization results

The proximate, ultimate and HHV tests for the feedstock are shown in table 1.

TABLE I. *A. TORTILIS* PROPERTIES FROM ULTIMATE, PROXIMATE AND CALORIMETRIC ANALYSES

Ultimate analysis						Proximate analysis				**HHV** MJ/kg
	C	H	N	S	O*	MC	VM	Ash	FC	
%	41.5	5.2	1.2	~	52.1	3.7	76.5	3.9	19.6	17.3

*Calculated by difference

The carbon content of feedstock to be used for thermochemical purposes is the most significant since it has a direct influence on the calorific value of derivatives. The carbon content is less than that reported for *Acacia Holosericea* (44%) [1]. *A. tortilis* also has a higher N content of 1.2% compared to 0.25% in *A. Holosericea*; in both acacias, S was not detected. High N contents are typical in acacias which thrive in poor soils due to their N fixation capabilities, while negligible S composition gives a sulphur free biofuel. From proximate analysis, the ash in both *A. tortilis* and *A. Holoricea* is comparable at 3.90% and 3.91% respectively; it is also lower than the critical fouling and slagging ash value of 6%. *A. tortilis* however, has a higher VM composition (76.5%) than *A. holoricea, A mangium and A auriculiformis (*65.32%, 65.2% & 65.37%*),* which signifies that higher recoveries of boiooil fom condensable gases are expected for the *A. tortilis* during pyrolysis [1], [8]. The HHV of *A. tortilis* (17.3MJ/kg) is also lower that of *A. Holosericea* (18.13MJ/kg) and pine (17.6MJ/kg) (but marginally higher than the averages of *Acacia Auriculiformis* (17.13MJ/kg) and *Acacia Mangium* (17.03MJ/kg) for 3 parts of the trunk. As concluded by all these researchers on the acacias, *A. tortilis* is also found suitable for thermochemical conversions like pyrolysis.

B. Pyrolysis

The optimum pyrolysis temperature for a high bio-oil yield was found at 550ºC, which is slightly higher than figures obtained for other woody biomass species like pine (500ºC) [14], [15]. Bridgwater (2011), however, claims that the maximum yield from lignocellulosic biomass is achieved between 480ºC and 520ºC, with grasses occupying the lower end and woody biomass the higher end [16]. Since the experiments for the *A.tortilis* were carried out at 50ºC intervals, it is possible that the actual maxima is between 500 and 550ºC. The variation of char, boioil and gas yields with temperature is shown in Fig 2.

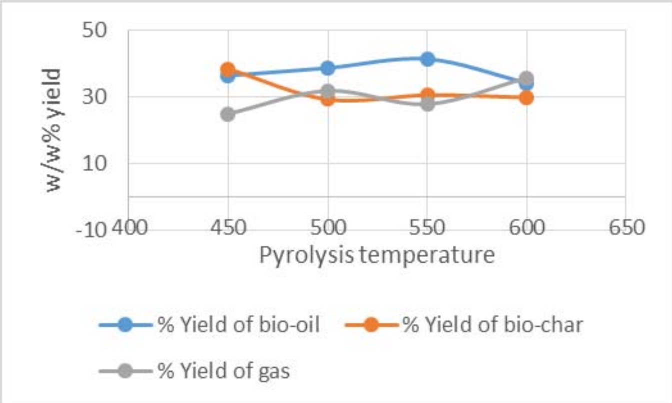

Fig 2: Variation of bio-oil, bio-char and gas yields with temperature

The optimum condenser temperature for *A. tortilis* was found at 125ºC as shown by the SG values in Fig 3, although it was not very different from the SG of the heavier oil at 140 ºC. It is also interesting to note that the yield of the heavier oil is actually greater at 140ºC and 110ºC (table II), therefore in reality, the trade-off between the quality of oil produced and quantity should be considered.

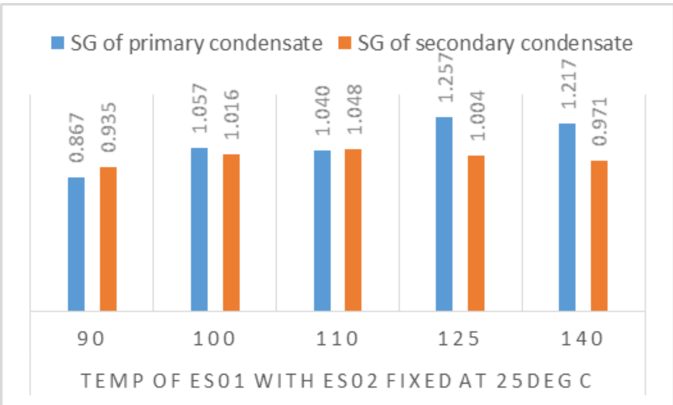

Fig 3. Specific gravity (SG) of primary condensate at various condenser (ES01) temperatures.

TABLE II. ACTUAL % YIELD OF HEAVIER OIL

ES01 Temp (°C)	90	100	110	125	140
Heavy oil yield	6.0%	5.4%	4.9%	2.8%	3.9%

C. *Product characteristics*

The other product properties tested for are catalogued in table III below, in comparison with properties of diesel, gasoline and light fuel oil, since prospective bio-oil uses might substitute these fuels. By the time of writing the paper, the flash and pour points had not yet been determined. Since the primary condenser (ES01) was the piece of equipment used to obtain some form of upgraded oil with lower aqueous composition, the heavier bio-oil fraction obtained from here at various temperatures is compared to the conventional fuels.

TABLE III. PROPERTIES OF PRIMARY CONDENSATE OIL COMPARED TO CONVENTTIONAL FUELS

		pH	**Viscosity (mPa.s)**	**HHV (MJ/kg)**	**SG**
A. tortilis bio-oil at ES01 Temp °C	90 °C	3.27	2217.6	4.310	0.867
	100 °C	3.64	4804.8	21.412	1.057
	110 °C	3.84	Too little to measure	23.610	1.040
	125 °C	3.23	Too little to measure	26.191	1.257
	140 °C	3.12	Too little	36.809	1.217
Conventional diesel		-	2178	43-45	0.844
Light fuel oil		-	-	42-44	0.85-0.910
Heavy fuel oil		-	>17800 at 50°C	40	0.940-0.989

The pH increases with temperature until 110ºC, then decreases until 125 ºC. The average pH (3.42) is still considerably higher than the 2.5 estimated in literature for woody bio-oils [16]. This implies that *A. tortilis* bio-oil generally has a higher pH, making it relatively less corrosive than other bio-oils. The secondary condenser oils all had a higher pH, viscosity and SG compared to the primary condenser oils. Better still, besides the primary condensate at 90ºC, the rest did not require any combustion aid for the calorimetry test and the HHV increased with increasing condenser temperature. However, the viscosity also had signs of increase. Assuming that the initial trend of viscosity doubling at every 10oC interval, the estimate for 110ºC, and 125ºC and 9609.6, 24.024 mPa.s, which could make sense considering the thick bitumen like texture of the 125ºC bioil. However, the 140ºC bio-oil should not be very different from that at 125oC, considering the almost similar texture and flow. The viscosity of the best quality oil obtained at 125ºC would then be way higher than the viscosity of diesel (2178mPa.s) in the range of HFO (17,800-36,000 at 50ºC). The viscosity of bio-oil at 90ºC and 100oC primary condenser temperature is within the range mentioned by Bridgwater (2011) and Bridgwater (2018), of 30-12000mPa.s; though the author gives room for bio-oils of higher viscosities [11], [16]. Bridgwater (2018) recommends dilution of bio-oils with solvents to reduce its viscosity and stabilizes it, making it compatible for use in slow and fast diesel engines [11].

The highest calorific value is actually obtained at 140ºC (36.809MJ/kg) instead of 125ºC where the highest SG had been obtained, suggesting this is the best primary condenser oil. The HHV is comparable to the 40,000MJ/kg in HFO, suggesting possible direct use in slow engines after adding a solvent to stabilize the oil. For fast diesel engines however, the oil would need to be dissolved in a sufficient solvent to make it compatible for a diesel blending.

The primary condensate sample at 125^{o}C and the corresponding secondary condensate were taken as the representative samples for the GCMS,. A total of 95 and 76 compounds were indentified in the primary and secondary condensate respectively. This is typical of bio-oil, which usually contains more than 300 oxygenated compounds [17]. It is usually difficult to indentify all of the compounds using the conventional GCMS due to the complex layers of bio-oil therefore a GC×GC is recommended for further resolution in 3D, to show most of the compounds. The compounds with the highests areas fractions are shown, for both condensates, are shown in Table IV.

TABLE IV. COMPOUNDS WITH THE HIGHEST RELATIVE ABUNDANCE IN *A. TORTILIS* BIO-OIL

Primary condensate		**Secondary condensate**	
Compound	*Relative % abundance*	*Compound*	*Relative abundance*
Creosol	7.759	Phenol, 2-methoxy-	15.638
Phenol, 4-ethyl-2-methoxy-	5.325	Phenol, 2,6-dimethoxy-	12.377
Phenol, 2,6-dimethoxy-	5.120	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-	7.533
Phenol, 2-methoxy-	4.847	Hydroquinone mono-trimethylsilyl ether	6.052
Benzene, 1,3-bis(1,1-dimethylethyl)-	4.390	4-Methoxy-2-methyl-1-(methylthio)benzene	5.103
Phenol, 2,4-bis(1,1-dimethylethyl)-	4.254	Benzene, 1,3-bis(1,1-dimethylethyl)-	3.960
5-tert-Butylpyrogallol	3.302	2-Cyclopenten-1-one, 3-ethyl-2-hydroxy-	3.764
Phenol, 2-methoxy-4-(1-propenyl)-, (Z)-	3.022	Cyclohexanol, 2,2-dichloro-1-methyl-	2.138

Evidently, creosol is the most abundant in the primary condensate while Phenol, 2-methoxy and Phenol, 2, 6-dimethoxy are the most concentrated in the secondary condensate. The secondary condensate could become the source of useful chemicals since it is not useful for fuel and has good proportions of selected compounds; while the primary condensate is taken up for fuel. The chief concern however, will be the small yields of the primary bio-oil. One key observation was that there was a lot of water in the secondary condensate. If the *A. tortilis* residues are heated in an over instead of just the solar drying, the bound moisture can also be driven away giving a better quality oil. More experiments will also be done with the secondary condenser at temperatures just above and just below 100^{o}C and the tertiary condenser at ambient temperature to try and increase the fraction of high quality bio-oil.

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CONCLUSION

This research has demonstrates that *A. tortilis* is a good bio-energy feedstock whose bio-oil can have a calorific value comparable to that of HFO. The bio-oil could be used is moderate-slow engines with moderate upgrading. However, blending with diesel is the feasible route is the oil is to be used in fast diesel engines. In both cases, the bio-oil has to be diluted with a solvent and the proportions depend with the end application and the intend value of viscosity. Tests have to be done to establish these proportions and their effect on the calorific value of the final product. One major problem in the application of pyrolysis oil is that there have not been adequate demonstrations on the application of the bio-oil, stationary engines for instance. Perhaps, governments in countries like Botswana might want to invest in such research, development and demonstrations. The advantage in this case would be consistency in the feedstock type, given the vas availability of the acacia encroacher bush. It is also recommended that further tests be done to establish the particulate composition and flash point of the bio-oil, which will further inform on the suitability of the oils as engine fuels. Furthermore, the supply chain capacity of this waste resource has to be established, especially in areas where bio-energy projects are intended. An overall feasibility assessment that goes beyond a technical study like this one should also be done to cover socio-economic and environmental aspects. The economic feasibility study can consider auto-thermal designs that can derive all their energy requirements using from partial oxidation or burn the char and/ or gas.

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